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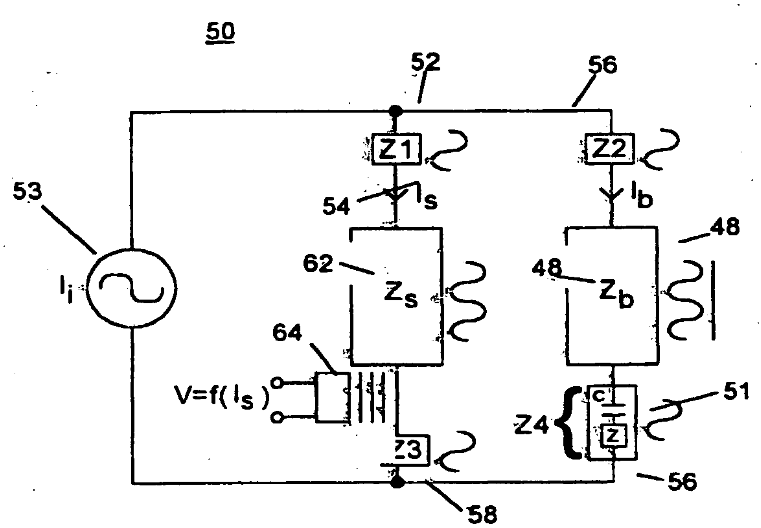
(54) Title: METHOD AND APPARATUS FOR MEASUREMENT OF ELECTROCHEMICAL CELL AND BATTERY IMPEDANCES



(57) Abstract: A battery's impedance is measured by a technique that normally uses a current divider network which is connected to the battery. The circuit used according to this technique has a current generator (53) producing a regulated current signal (Ii) and has one or more sensing impedances (Zs) which are normally positioned electrically parallel, or in some alternate embodiments in series, with the battery. A DC-blocking capacitor prevents the battery voltage from draining into the one or more sensing impedances (Zs). A magnetic field sensor or comparable device measures the magnitude and/or phase of current passing through the sensing impedances. Substitution of a number of calibrated impedances into the circuit in place of the battery permits an initial mathematical computation of the battery's impedance utilizing this technique. Thereafter battery impedances can be computed with the current without using calibrated impedances.

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Method and Apparatus for Measurement of Electrochemical Cell and Battery Impedances

Background

This invention relates to techniques for measuring impedance in electrochemical cells. More particularly, the invention is directed to apparatuses and methods used for taking internal impedance measurements of electrochemical batteries and cells with improved sensitivity and noise/electromagnetic immunity as compared to currently existing methods.

Electrochemical batteries and cells have very low internal impedance. This is true in different types of cells, including those based on either lead acid or nickel cadmium chemistries for which impedances can be on the order of milliohms (mΩ). For this reason, an effective method for measuring impedance must be highly sensitive to small impedance values while being immune to noise and electromagnetic circuit interference. Prior methods of impedance measuring normally utilize one of five different types of electrical circuits: (1) bridge circuits; (2) voltage dividers; (3) 4-wire connections; (4) short circuits; and (5) time constant circuits. However, each of these methods is limited by the inherent characteristics of the particular circuit type used in performing the impedance measurement.

Bridge circuits are commonly used to sense impedance changes in batteries. Such a bridge circuit **20** is depicted in FIG. 1, which shows the basic configuration of a circuit of this type which is powered by an AC voltage source V_i. These circuits generally include impedance elements **22** that are located along first and second current paths **24** and **26**, the impedance elements **22** being located on either side of voltage divider points where the voltages V_A and V_B can be measured. For battery impedance measurements, one of the impedance elements **22** in the bridge represents the battery being measured. The output of the bridge, V_o, is the potential difference between V_A and V_B. The voltages V_A and V_B are related to the input voltage, V_i by the relation

$$V_A = V_i \left[\frac{Z3}{Z1 + Z3}\right] \text{ and } V_B = V_i \left[\frac{Z4}{Z2 + Z4}\right],$$

under the condition that V_o is equal to zero (i.e. $V_A = V_B$), so that

$$(Z1)(Z4) = (Z2)(Z3).$$

For example, one way of using this circuit is to make one of the impedance elements **22** adjustable and adjust the value of the impedance until V_o is equal to zero. The problem with this type of operation is that it requires continuous adjustment of the element for each frequency at which the measurement is made. This is because battery impedance is not constant over the frequency spectrum of interest.

An automated system for handling such a procedure is complex and difficult to implement. This circuit is typically used by picking nominal values of the three known impedance elements **22** to maximize the output voltage swing as the battery impedance changes through the sweep of frequencies and usable life. The sensitivity of the output is maximized when Z2 = Z3 and Z1 = Z4. This implies that one of the impedance elements **22** must have a value that is the complex conjugate of the battery impedance.

Another limitation of bridge circuits relates to the fact that since internal impedance is very low for most cell types, voltage drops across the battery will also be very low. Fixing the values of all but one impedance element **22** and allowing only this battery impedance element to change implies that either V_A or V_B will remain constant. The bridge **20** reduces to a voltage divider for changes in the battery impedance. The output voltage is inversely proportional to changes in the battery impedance. Thus, as the impedance of the battery increases, output voltage becomes smaller. To get sufficiently large voltage drops at the output, a large amount of current is required. For example, if the magnitude of the battery impedance were 5mΩ, a 1A current would be required to produce a 5mV drop at the output.

Such a condition would place a high gain requirement on any sensing amplification equipment connected at the output of the bridge circuit. For example, the input impedance of such an amplifier would be the impedance of the bridge circuit **20** and would be very low due to the low battery impedance. Where such low input impedances are involved, such as those below 1Ω, amplifiers become highly susceptible to electrical field noise, whether self-generated or from other sources. This condition is compounded where the input signal is also very low. Adverse interference effects can be expected regardless of whether BJT or FET input stages are used. Although the addition of a transformer across V_o is typically recommended in cases of low input impedance, the addition of such a device tends to contribute to circuit impedance, lowering the circuit's sensitivity. Alternatively, where a sufficiently high turns ratio is present, an added transformer can reduce the bandwidth of the output signal produced.

Since bridge circuits do not easily permit impedance sensing without adjustment of the known impedance elements **22**, the circuit has no more sensitivity than the voltage divider circuit. Thus, such circuits are normally only usable in laboratory settings where the impedance elements can be adjusted.

A second commonly used technique for impedance measuring uses a voltage divider circuit, which is typically preferred over bridge circuits when adjustment of impedance is not required. A voltage divider circuit **28** used for battery impedance measurements is shown in FIG. 2. The circuit **28**, like most designs of this type, is driven by an AC current source **30** since voltage levels are typically in the range of millivolts and current in the range of amperes and thus amperage is easier to regulate than voltage. The circuit includes a sensing impedance Z_s and a battery impedance Z_b in a series loop **29** with the AC current source. Each sensing and battery impedance has a respective sensor **31** that connects to the series loop **29** at the respective impedance's point of positive and negative potential. Each sensor **31** is separated from the series loop **29** by capacitors **32** used to block the battery's DC signal. This technique

involves two measurements: (1) measurement of the voltage V_s across a sensing impedance Z_s, permitting measurement of the loop current given the known size of Z_s; and (2) measurement of the voltage V_b across the battery **34** being measured.

Voltage divider circuits used to measure battery impedance are limited by the same disadvantages as bridge circuits. Like bridge circuits, voltage measurements are taken in the millivolt signal level since batteries have very low impedance. Thus, voltage divider circuits, like bridge circuits, are susceptible to electrical field noise and have limited sensitivity.

A third technique utilizes a circuit known as a 4-wire or "Kelvin" connection. This is among the most frequently used techniques for measuring battery impedance and has been described in numerous patents and other references. The general configuration of a 4-wire connection **36** is shown in FIG. 3. In principle, this circuit is very similar to a voltage divider circuit, being driven by a current source **37**. But the 4-wire connection **36** does not have a sensing impedance Z_s. A battery **38** is interrogated with a current signal, and the voltage drop V_b across the battery **38** is measured with a sensor **31** separated from the battery nodes by capacitors **32**. As indicated above, for most lead acid and nickel cadmium cells, the internal impedance Z_b is very low. This means that the battery **38** will be driven with amperes of current, and output signals will be on the order of millivolts of potential.

Most of the problems associated with bridge circuits and voltage dividers also apply to 4-wire connections. In fact, U.S. Patent No. 5,821,757 to Alvarez et al. specifically addresses the problem of reducing electromagnetic interference (EMI) that adversely affects the 4-wire connection described in U.S. Patent No. 5,281,920 to Warst with the addition of twisted, shielded-paired wires. Other attempts to reduce system noise have included the incorporation of ground isolation, the selection of driving frequencies away from known sources of electric field noise, and the combined techniques of windowing and averaging.

The fact that there is a need for each of these attempted remedies demonstrates the inherent limitations of this type of circuit. In such a system, larger output signals require a larger input current signal. For example, output signals on the order of tens of millivolts require input signals on the order of tens of amperes. However, sensitivity tends to be inversely related to the impedance of a battery. Since larger cell sizes ultimately lead to progressively smaller internal impedances, then for progressively larger cells, output voltages produced using the 4-wire technique tend to be smaller for the same input current. It follows that this technique is generally inadequate for using in a broad range of cell sizes.

Another technique used to measure battery impedance is the short circuit configuration. This configuration is less common than others described above and has been used in applications where internal impedance magnitudes have been on the order of hundreds to thousands of ohms, such as in lithium iodine batteries used in pacemakers and related devices. A simplified illustration of a short circuit **40** is shown in FIG. 4. The circuit has a switch **41** connected to the positive node of a battery **42** having an impedance Z_b. The battery's negative node is grounded, while the switch **41** connects the positive node to a current mirror **43** and to ground **45**. This technique simply involves taking a voltage measurement on the unloaded battery **42** followed by a measurement of the short-circuited current to calculate a measure of the battery's internal impedance Z_b. The short circuit is only applied long enough to get an accurate enough measurement of the discharge current.

Although this technique is useful for calculating impedance in small, lithium iodine batteries, other larger battery types, including larger lithium iodine and most lead acid batteries, pose a serious explosion hazard when similarly short circuited. This technique is also limited in that it can only be used to get a bulk number to represent the battery's internal impedance, which eliminates all phase and frequency related information.

One additional technique that is commonly used to measure battery impedance is the time-constant method. As demonstrated in the example circuit in FIG. 5, this method is based on the concept of an RC time response of a battery **44** where R is contributed from a battery **46** and a capacitor **45** is a selected known value C. The battery is connected between ground and a normally-open switch **47** which is connected through capacitor **45** to ground. The charge V_c across the capacitor **45** can be monitored through operational amplifier **49**. In operation, switch **47** is closed, causing the battery voltage V_b to discharge through battery resistance R_b to charge capacitor **45**. The time it takes to charge the capacitor **45** to the voltage V_b is used to determine battery resistance R_b since the capacitance C of capacitor **45** is known and the time $\tau = R_bC$.

This method has been incorporated into lithium iodine cells used in medical devices such as pacemakers. It includes switching a battery into a circuit with a parallel capacitor and then measuring the time response to determine the time constant, $\tau = RC$.

As with other techniques, the battery's internal impedance is assumed to be a resistive element and the resulting measurement is reduced to a bulk number. No information about phase or frequency contributions is measured or determined. The technique is also limited in that there is a necessary tradeoff between capacitor size and processing speed of the detection circuit. A larger capacitor requires a larger amount of energy to be drawn from the battery, while the smaller the capacitors, the less time there is for the detection circuit to determine the time constant, affecting the sensitivity of the circuit. This relative dependence on the capacitor's size ultimately affects the circuit's sensitivity.

Most prior art methods of measuring internal impedance in batteries rely heavily on taking voltage measurements. Due to the very low impedance magnitudes involved, output signals are normally expected in the range of millivolts. This means that in order for most prior art methods to be operable, high gain amplifiers having a combination of low voltage signals and low input impedances to the amplifier must be used, implying a high level of susceptibility

to noise and EMI. The related apparatus sensitivities of most prior art methods are also related to the impedance of the measured battery. As battery cells become progressively larger, internal impedance becomes smaller. Voltage measurements in turn become progressively smaller, thereby reducing the sensitivity of the measuring circuit. Although increasing input current can improve the output signal, such a step can be prohibitive since a magnification from amperes to tens of amperes may be required to achieve the desired effect.

Frequent measurements at high current levels not only impose a higher power requirement on the circuit, but also subject the battery to higher levels of energy. Such conditions can potentially contribute to heating and eventual disruptions in normal cell reactions. As confirmed by the number of past efforts to improve existing impedance measurement techniques, a new technique for measuring impedance is needed that is less sensitive to noise and EMI effects. Such a technique should also be less dependent on direct voltage measurements that are taken across the subject battery, while remaining usable for a variety of battery sizes and configurations.

Summary

In accordance with this invention, battery impedance Z_s of a battery is measured by a circuit, such as a current divider network which is connected to the battery. The circuit has a current generator producing a current signal I_i and has one or more sensing impedances Z_s which are normally positioned electrically parallel, or in some alternate embodiments in series, with the battery. A DC-blocking capacitor is positioned in series with the battery to prevent the battery voltage from draining into the one or more sensing impedances Z_s. A magnetic field sensor or comparable device for measuring the electromagnetic field produced by the current flowing through a wire, is then used to measure the current I_s passing through the sensing

impedances Z_s. Either the magnitude or the phase, or both, of I_s can be measured to arrive at a usable value.

Once the value of I_s has been determined, the value of the impedance is mathematically determined. This can be done, for example, by substituting a number of calibrated impedances having values Z_{cal1} through Z_{calN}, into the circuit in place of the battery and its impedance value Z_b. In one illustrative method, for example, the mathematical determination includes accounting for the effects of the combined circuit and connector impedances Z1 and Z2 which lead, respectively, into the parallel sensing and battery impedances Z_s and Z_b. An additional accounting is made for the effect of the combined circuit and connector impedance Z3 leading out of the sensing impedance Z_s and the combined circuit, connector and blocking capacitor impedance Z4 leading out of the battery impedance Z_b. This results in the relationship:

$$Z_b = I' (Z_s + Z1 + Z3) + (Z2 + Z4)$$

where

$$I' = \frac{I_s}{I_i - I_s},$$

so that:

$$Z_b = \frac{I_s}{I_i - I_s}(Z_s + Z1 + Z3) + (Z2 + Z4)$$

where the values of Z1, Z2, Z3, and Z4 may be unknown. In this example of the technique, two calibrated impedances Z_{cal1} and Z_{cal2} are substituted into the circuit for the battery impedance Z_b where:

$$Z_x \equiv Z3 + Z1 + Z3 \text{ and } Z_y \equiv Z2 + Z4$$

so that

$$Z_b = I' Z_x + Z_y$$

resulting in an I_s value of I_1 when Z_{cal1} is substituted for Z_b and resulting in an I_s value of I_2 when Z_{cal2} is substituted for Z_b so that

$$Z_x = \frac{Z_{cal1} - Z_{cal2}}{I_1 - I_2},$$

and so that

$$Z_y = \frac{I_2 Z_{cal1} - I_1 Z_{cal2}}{I_1 - I_2},$$

with the final step in this example being the simple determination of the value of Z_b by substitution into the equation

$$Z_b = I' Z_x + Z_y.$$

While the illustrative embodiment of this invention utilizes two calibrated impedances Z_{calN}, it will be appreciated that a larger number of calibrated values may be used to achieve the necessary measurement of Z_b as will be explained further in the following Detailed Description of the Preferred Embodiments. It will also be appreciated that, as reflected in the series embodiment of the incorporated circuit described below as an alternative embodiment of the invention, various circuit configurations are also possible in carrying out the disclosed impedance measuring technique and are fully contemplated as being within the scope of this invention. For example, the use of additional, parallel sensing impedances Z_s may be preferred and are contemplated.

Thus, the invention does not reside in any one of the features of the impedance measuring apparatus and method which is disclosed above and in the Detailed Description of the Preferred Embodiments and claimed below. Rather, this invention is distinguished from the prior art by its particular combination of features disclosed. Important features of this invention have been disclosed in the Detailed Description of the Preferred Embodiments of this invention which are shown and described below, to illustrate the best mode contemplated to date of carrying out this invention.

Those skilled in the art will realize that this invention is capable of embodiments which are different from those shown, and the details of the structure of the impedance measuring apparatuses and the details of the disclosed impedance measuring methods can be changed in various manners without departing from the scope of this invention. Accordingly, the drawings

and description are to be regarded as illustrative in nature and are not to restrict the scope of this invention. Thus, the claims are to be regarded as including such equivalent apparatuses and methods as do not depart from the spirit and scope of this invention.

Brief Description of the Drawings

For a more complete understanding and appreciation of this invention and many of its advantages, reference will be made to the following, detailed description taken in conjunction with the accompanying drawings wherein:

FIG. 1 depicts a typical bridge circuit configuration of the type commonly used in one impedance measuring technique of the prior art;

FIG. 2 depicts a typical voltage divider configuration of the type commonly used in an additional impedance measuring technique of the prior art;

FIG. 3 represents a basic 4-wire configuration of the type used in the prior art;

FIG. 4 depicts a typical a short circuit configuration used in the prior art;

FIG. 5 is a prior art time constant configuration circuit;

FIG. 6 is a general form of a proposed circuit which is according to the principles of this invention;

FIG. 7 is a general form of a proposed circuit with connector, wire, and capacitor impedance values denoted before and after both the sensing impedance and the battery impedances;

FIG. 8 represents a magnetic interface for sensing current I_s according to the principles of this invention;

FIG. 9 is an alternative series embodiment of a proposed circuit according to the principles of this invention;

FIG. 10 is an electrical schematic of a prototype circuit implementing the invention concept; and

FIG. 11 is a graphical representation of impedance of a nickel cadmium battery during discharge.

Detailed Description of the Preferred Embodiments

Referring to the drawings, identical reference numbers and letters designate the same or corresponding parts throughout the several figures shown in the drawings.

The proposed technique for making impedance measurements deals directly with the limitations of prior art measuring techniques. As noted in the Background above, most previous impedance measurement techniques rely on voltage measurements made across the battery and/or sensing impedance. These measurements are in the order of millivolts, driven at amps of current through milliohms of impedance. Thus, it is very difficult to measure such current levels by merely measuring the voltage across a sensing impedance Z_s. For example, as noted in the Background, a simple voltage measuring device is highly susceptible to the effects of noise, EMI, and the current drain of the battery itself. However, an alternate way of measuring a current I in given leg of an electrical circuit is to measure the magnetic field generated at a sensing branch of the circuit. Such a current I can be appropriately measured either by its magnitude or change in its phase angle or both.

FIG. 6 depicts a general form of a circuit which may be used to calculate a battery's impedance according to the proposed technique. The circuit has the general construction of a current divider network. C represents the capacitance of a DC-blocking capacitor **51** that is selected large enough for the AC range of interest. Selection of an appropriate size of capacitor **51** is dependent upon the lowest frequency level, or "half power frequency," which the capacitor allows to pass through it, determined by the formula

$$C = \frac{1}{2\pi\ Z_s\ f_h}$$

where C is the capacitor's capacitance value and f_h is the half power frequency, and Z_s is the magnitude of this impedance and does not include its phase angle. Without the DC-blocking

capacitor 51, current from the battery 48 would drain into the sensing impedance Z_s. Ideally, Z_s is kept as close as possible to the anticipated impedance of the battery to be measured.

Z_b represents the battery impedance that is being measured by the circuit, I_i represents the input current signal and I_s represents the sensing impedance current. Additionally, I_b represents the AC current through the battery 48, though the actual current in the cell may contain a DC component if a load is connected to the battery 48. In this embodiment of the proposed circuit, current I_i travels from a current source 53 through a current signal path 50 to a current dividing connector 52 where it splits into portion I_s, flowing through sensing current path 54, and into portion I_b, flowing through battery current path 56. The sensing current and battery current paths 54 and 56 eventually re-converge at current converging connector 58. If measurements are done online, the AC current signal can be choked with an appropriate AC choke 60, if necessary, so the load impedance, Z_L is much larger than Z_s and Z_b.

To determine the battery impedance, Z_b, requires recognition of the basic relations

$$I_i = I_s + I_b$$

and

$$Z_b = \frac{V_b}{I_b}.$$

Neither the battery voltage V_b nor the sensing impedance voltage V_s are measured directly. However, since the I_s and I_b branches are parallel,

$$V_b = V_s = I_s Z_s$$

then

$$Z_b = \left(\frac{I_s}{I_i - I_s}\right) Z_s.$$

When battery sizes become very large, cell internal impedance becomes very small, so that impedance contributions from connectors and wires cannot be ignored. Thus, the circuit must be remodeled to include these additional impedance elements. Each of these particular elements is included in FIG. 7, with the load being omitted. In this particular embodiment of the circuit, the impedance resulting from capacitance C of DC-blocking capacitor 51 is lumped

with the impedance of the connector and local segment of the battery-current path **56** as Z4. Z1, Z2, and Z3 represent the connector and wire impedances of sensing element **62** and battery **48**. Z_s is a known value, and as noted above, is ideally kept as close as possible to the impedance of the battery to be measured. However, unlike Z_s, the values of Z1, Z2, Z3, and Z4 are not known explicitly. For this circuit, it is known that

$$V_s = V_b$$

which can be written as

$$I_s(Z_1 + Z_s + Z_3) = I_b(Z_2 + Z_b + Z_4).$$

The definitions

$$Z_X \equiv Z_s + Z_1 + Z_3 \quad \text{and} \quad Z_Y \equiv Z_2 + Z_4$$

allow for the relation

$$Z_b = \left[\frac{I_s}{I_i - I_s}\right] Z_X + Z_Y .$$

Further, the definition

$$I' \equiv \frac{I_s}{I_i - I_s}$$

allows for the relation

$$Z_b = I' Z_X + Z_Y .$$

For this equation, I' is known and measured. However, Z_X and Z_Y are not precisely known, and may not be known at all. Z_b is the value that must be determined.

As an example of this technique, the values of Z_X and Z_Y can be determined experimentally using two different calibrated impedances, Z_{cal1} and Z_{cal2}. The example procedure involves removing the battery **48** from the circuit and replacing it with Z_{cal1} first and then Z_{cal2}. It will be appreciated, however, that removal of the battery **48** may not always be necessary in order to complete the required measurements according to the invention, for example if the values of Z1, Z2, Z3 and Z4 are small in relation to Z_b and Z_s, or if the values of Z1, Z2, Z3 and Z4 are already known. In this example, a measurement of I_s is made for each of

the two calibrated impedances Z_{cal1} and Z_{cal2}. This results in two equations derived from the previous equation for Z_b,

$$\begin{aligned} Z_{cal1} &= I_1 Z_X + Z_Y \\ Z_{cal2} &= I_2 Z_X + Z_Y \end{aligned}$$

Solving for Z_X and Z_Y leaves the relations,

$$\begin{aligned} Z_X &= \frac{Z_{cal1} - Z_{cal2}}{I_1 - I_2} \\ Z_Y &= \frac{I_2 Z_{cal1} - I_1 Z_{cal2}}{I_1 - I_2} \end{aligned}$$

Once Z_X and Z_Y are determined, the battery **48** can be placed back into the circuit and the previous equation

$$Z_b = I' Z_X + Z_Y$$

can be used to later determine Z_b after a value for I_s is determined.

It will be appreciated that, while the impedance determination of this example is made using two impedance values, it is also possible to use more than two calibration values, and this possibility is fully contemplated to be within the scope of the invention. For example, given the relation

$$Z_b = I' Z_X + Z_Y,$$

in which Z_x and Z_y are not precisely known, a number N of known calibration impedances Z_{cal1} through Z_{calN} can be substituted for Z_b in the circuit, allowing for a measurement of I_s to be made for each of the calibration impedances leaving N separate relations

$$\begin{aligned} Z_{cal1} &= I_1 Z_x + Z_y \\ &\vdots \\ Z_{calN} &= I_N Z_x + Z_y, \end{aligned}$$

which, depending on the range of the calibration impedances, can be solved linearly, piecewise-linearly, or nonlinearly for Z_x and Z_y.

It should be noted that, unlike the prior art techniques discussed above, the voltage drops across Z_s and Z_b are never measured directly. Once the circuit is calibrated for Z_x and Z_y, the battery **48** can be placed back into the circuit for the determination of Z_b from the measurement of I_s.

Detection of I_s is accomplished by magnetically coupling I_s with a magnetic field sensor **64** such as a Hall effect or a magnetoresistive sensor or any other device which can determine the magnitude and phase of a magnetic field. This is possible if Z_s is an electrical conductor such as copper. An appropriate magnetic interface **66** is depicted in FIG. 8. The figure shows how the magnetic interface links the sensing current, I_s to the magnetic sensor **64**. The interface includes a ferromagnetic core **68** which is coupled to the magnetic field sensor **64** and which need not be wound. The sensing current I_s travels along the sensing impedance Z_s throughout the ferromagnetic core **68** resulting in a magnetic flux **70**. The size and shape of the conductor Z_s should be selected to maximize sensitivity of the current change when the battery impedance Z_b changes and maximizes the flux linkage to the magnetic circuit.

Z_s represents a single turn winding on the magnetic core **68** and the magnetic sensor **64** sits in the air gap that dissects the core path. The magnetic flux density that the magnetic field sensor **64** is exposed to is given by the equation

$$B_{gap} = \frac{\mu_0 \mu_{core}}{\ell_{core} + \mu_{core} \ell_{gap}} I_s .$$

This equation assumes the cross sectional area of the air gap is the same as the core. B_{gap} is the magnetic flux density of the air gap and ℓ_{gap} is the effective gap length. Also, ℓ_{core} is the effective core flux path length, μ_{core} is the core permeability factor and μ_0 is the permeability of free space. It should be noted that this equation was derived under static assumptions and nonlinear and dynamic properties such as hysteresis and core saturation are considered negligible factors for purposes of this invention description. The equation shows that the air gap

length is the dominant factor for the sensitivity of the flux density to the sensing current I_s. If a large enough current is used and if the magnetic field sensor **64** is sufficiently sensitive, a core **68** may not be necessary.

The choice of magnetic field sensor **64** must include considerations such as the sensor's ability for mounting in the core path and the ability to provide sufficient sensitivity to detect the sensing current I_s. Some suitable types that have been successfully implemented include Hall effect and anisotopic magnetoresistive (AMR) sensors which are readily available. AMR sensors, such as the Honeywell HMC1001, have demonstrated greater levels of sensitivity than Hall effect sensors, such as the Optek OHN-xx, for operation in small magnetic fields. AMR sensors also offer a much wider bandwidth at approximately the same cost as Hall effect sensors. Other alternative sensor types may present problems due to cost, bandwidth, and size. Some alternatives, such as the use of secondary windings as the magnetic sensor **64**, present an additional limitation in that they tend to introduce impedance into the circuit and constrain the bandwidth. However, it is contemplated that additional, satisfactory magnetic field sensors will be developed over the years for use according to this invention.

Advantages of the invention over previous impedance measuring techniques include greater sensitivity and greater immunity to noise and EMI. In the proposed circuit, sensitivity is controlled mainly by the selection of the sensing impedance and the gap size of the core **68**. The fact that no potential measurements are taken across low voltage and impedance sources results in greater immunity to noise and EMI. Most previous methods require that measurements of voltage drops be made across the battery **48** and/or sensing impedance. In comparison, the proposed technique requires only that a current measurement be made.

For prior art methods of measuring battery impedance, such as the 4-wire circuit, the voltage drop across the battery will become progressively smaller as cell sizes increase. This results in the circuit becoming increasingly less sensitive as the magnitude of each

measurement fails. It follows that the change in sensitivity is dependent on the internal impedance of the battery being monitored. Since the technique proposed by this invention measures only current with proper selection of a sensing impedance, sensitivity becomes independent of the measured internal impedance. Thus, given the proper selection of the sensing impedance, circuit sensitivity using the technique of this invention will be approximately the same in both large and small capacity cells. In addition, the overall measurement sensitivity of the disclosed technique is superior to that of previous measurement techniques. When, by way of example, an AMR sensor is used in conjunction with the technique of this invention, sensitivity has been shown experimentally to improve 26 times over the level of a prior art 4-wire circuit. Reducing the core air gap size may further increase sensitivity of this technique.

A further advantage of the invention relates to inherent noise and EMI limitations of previous techniques, such as the 4-wire circuit. In such previous techniques, sensing amplifiers are required to amplify signals in the range of millivolts from a low impedance source, the battery, or sensing impedance. Such amplification typically requires the use of transistor amplifiers, such devices being highly susceptible to electric field noise sources when the input source impedance is low.

In the proposed circuit configuration, sufficiently high current, typically in the range of milliamps or greater, is sensed by the magnetic interface **66** and is more immune to noise and EMI than voltage gain amplifiers would be. The sensing amplifier for this circuit is connected to the magnetic field sensor **64**, which, as noted above, has much higher impedance and voltage levels due to the improved sensitivity. For example, a Honeywell HMC1001 has a source impedance of 850Ω while, with other AMR sensors typically having source impedances in the range of hundreds to thousands of ohms.

It will be further appreciated that alternate forms of the disclosed circuit may be implemented with the proposed technique and are contemplated to be within the scope of this invention. One such alternate form of the proposed circuit is depicted in FIG. 9 and can be a voltage driven circuit having a voltage source 59 and also having a magnetic coupling in series with the battery **48** as shown in the figure. In this embodiment, the DC-blocking capacitor **61** is positioned in series between the battery impedance Z_b and sensing impedance Z_s. According to the proposed technique, an impedance measurement of the battery **48** would be accomplished first by noting that

$$V_i = V_b + V_s$$

and by noting that the sensing current I_s, which in this embodiment is also the battery current, can be expressed by the relation

$$I_s = \frac{V_i}{Z_b + Z_s}.$$

It would then follow that

$$V_i = I_s (Z_b + Z_s)$$

and

$$Z_b = \frac{V_i - I_s Z_s}{I_s}.$$

Thus, implementation of this circuit embodiment requires knowledge of the source voltage V_i, sensing impedance Z_s, as well as measurement of the sensing current I_s. In practice, this configuration is capable of making impedance measurements that are similar to other embodiments of the invention. However, unlike other embodiments, this specific configuration of the proposed circuit requires the inclusion of a voltage source V_i which must maintain potential magnitudes on the order of millivolts. Unlike other circuit configurations of this invention, this embodiment requires that for progressively larger battery cells, the voltage source V_i must become progressively smaller in order to maintain operability. Regulation of the voltage source V_i may become increasingly difficult for smaller battery impedances without an increase in the level of current delivered.

FIG. 10 is a schematic illustration of an example prototype circuit **72** incorporating the invention that can be used to collect battery impedance data from lead acid, nickel-cadmium and lithium battery cells. The circuit **72** is designed to be used with a PC based data acquisition (DAQ) board. The DAQ board is used to inject a waveform (V_{DAQ}) into the circuit at input **71** and toggle the set/reset circuit **82** of the AMR sensor with a signal ($V_{S/R}$) at input **73**. To sample the injected current waveform and sensed current waveform, the DAQ board has access to the feed current (V_{INJ}) and sensor response signal (V_{SENS}). The circuit section **74** in the upper left dashed box **75** represents the current source **76** and current divider circuit **78**. This section drives the current into the battery **79** and sensing element **81**. The injected waveform V_{DAQ} is passed to the signal amplifier U1 which in turn generates the current I_i. The differential amplifier U2 is used to detect and to determine the value of I_i as it exists at the negative node of resistor R8 and enters the current signal path **50**. A ferromagnetic core X1 of the magnetic sensor detects the value of I_s at the sensing impedance **81**.

The circuit section **80** in the upper right dashed box **83** represents the current sensing circuit that is linked to the sensing element via the ferromagnetic core X1 and the magnetic sensor S1. Within the magnetic sensor S1, the combined resistances of component resistors **85** change in proportion to the magnetic field they encounter at the sensing impedance **81**, with S1essentially comprising the ferromagnetic core X1. Within S1, a degaussing resistor **86** comprises a coil used for demagnetizing the component resistors **85** of the ferromagnetic core X1. In the event that an external magnetic signal interferes with the core's operation, the interference (magnetic offset) can be minimized by passing a positive voltage through the degaussing resistor **86** proximate to the component resistors **85**.

The circuit section of the bottom dashed box **82** of FIG. 10 shows the set/reset circuit used for minimizing the magnetic offset in the magnetic sensor. In the circuit, a signal $V_{S/R}$ at input **73** is electrically isolated from the rest of the circuit by an optical coupling U5. To

minimize a magnetic offset in the sensor S1, the signal $V_{S/R}$, which is normally on the order of +5V, is manually dropped to 0V for a duration of, for example, one second. While the optical coupling U5 electrically isolates the signal $V_{S/R}$ from the rest of the circuit, U5 still permits a mimicking +5V signal to pass from mimicking potential **88** through resistor R9 in response to each positive (+5V) condition for $V_{S/R}$. Mimicked signals are fed through four digital inverters U3, all of which may be contained on a single electronic chip allowing the signal to pass to a complementary MOSFET pair Q2. The MOSFET pair Q2 includes an N-channel MOSFET **90** and an E-channel MOSFET **92**, the pair functioning together as a combination toggle switch for effecting positive voltage through resistor **86**. All four digital inverters act in concert to alternate the positive conditions of the N- and E-channel MOSFETS in order to toggle positive voltage through the degaussing resistor **86** depending on whether $V_{S/R}$ is currently in its positive +5V condition. Minimizing the magnetic offset in this way insures that the magnetic sensor does not saturate or drift from the zero field point, helping to maintain high sensor resolution. This further enables the circuit to be used to collect impedance data on batteries while charging and discharging.

FIG. 11 is a sample plot of the impedance measured for a D-size, 4.3-Ahr nickel cadmium cell during discharge. Each point in the plot represents the cell impedance Z_b at different frequencies ranging from 1 Hz at the upper right end of the curve to 17.7kHz at the lower left end of the curve. The data for this plot was obtained using the prototype circuit of FIG. 10 on a nickel cadmium cell during a discharge cycle. It will be appreciated that those skilled in the art will normally test a particular battery at one or more frequencies to determine the battery's impedance Z_b at each frequency. It will be further appreciated that a subject battery may be tested at many selected frequencies to determine the condition of the battery in question, and that the invention permits those skilled in the art to perform testing across such frequency ranges as appropriate.

Those skilled in the art will recognize that the various features of this invention described above can be used in various combinations with other elements without departing from the scope of the invention. Thus, the appended claims are intended to be interpreted to cover such equivalent impedance measuring techniques that do not depart from the spirit and scope of the invention.

Claims

1. An apparatus for measuring impedance in an electrochemical cell comprising:

a current generator for producing an input current signal I_i along a current signal path in a current divider network;

said current divider network having at least a sensing current path and a battery current path, said sensing and battery current paths being in parallel to each other, each of said sensing and battery current paths also being in series with said current signal path, said current signal, sensing, and battery paths interconnecting with each other at a current dividing connector and at a current converging connector;

said sensing current path having a measurable sensing impedance Z_s located along said sensing current path, a connector-wire impedance Z_1 between said current dividing connector and said sensing impedance Z_s, and a connector-wire impedance Z_3 between said sensing impedance Z_s and said current converging connector, wherein a portion I_s of current signal I_i flows through said sensing current path;

said battery current path having a battery impedance Z_b located along said battery current path, a connector-wire impedance Z_2 between said current dividing connector and said battery impedance Z_b, and a connector-wire-capacitor impedance Z_4 between said battery impedance Z_b and said current converging connector, wherein a portion I_b of current signal I_i flows through said battery path;

a DC-blocking capacitor in series with said battery impedance Z_b and located along said battery current path to prevent said battery from discharging current through said sensing impedance Z_s;

said sensing current path also having a magnetic field sensor with a coupling attached thereto for measuring the magnitude and phase of I_s, thereby permitting mathematical determination of the value of Z_b.

2. The apparatus for measuring impedance in an electrochemical cell of Claim 1 in which the magnetic field sensor used for measuring the magnitude and phase of I_s is a magnetoresistive sensor magnetically coupled to the sensing current path.

3. The apparatus for measuring impedance in an electrochemical cell of Claim 1 in which the magnetic field sensor used for measuring the magnitude and phase of I_s is a Hall effect sensor magnetically coupled to the sensing current path.

4. The apparatus for measuring impedance in an electrochemical cell of Claim 1 in which the magnetic field sensor used for measuring the magnitude and phase of I_s is a magnetic resistive sensor magnetically coupled to the sensing current path;

said apparatus being further configured to experimentally determine Z_b by measuring the variable I_s when at least two different calibrated impedances Z_{cal1} through Z_{calN} are substituted for Z_b into the circuit of said apparatus.

5. The apparatus for measuring impedance in an electrochemical cell of Claim 1, said apparatus being further configured to experimentally determine Z_b from the measurement of the variable I_s when at least two different calibrated impedances Z_{cal1} through Z_{calN} are substituted into said current divider network of said apparatus.

6. An apparatus for measuring impedance in an electrochemical cell comprising:

a current generator for producing an input current signal I_i along a current signal path in a current divider network;

said current divider network having a sensing current path and a battery current path, said sensing and battery current paths being in parallel to each other, each of said sensing and battery current paths also being in series with said current signal path, said current signal, sensing, and battery paths interconnecting with each other at a current dividing connector and at a current converging connector;

said sensing current path having a measurable sensing impedance Z_s located along said sensing current path, a connector-wire impedance Z_1 between said current dividing connector and said sensing impedance Z_s, and a connector-wire impedance Z_3 between said sensing impedance Z_s and said current converging connector, wherein a portion I_s of current signal I_i flows through said sensing current path;

said battery current path having a battery impedance Z_b located along said battery current path, a connector-wire impedance Z_2 between said current dividing connector and said battery impedance Z_b, and a connector-wire impedance Z_4 between said battery impedance Z_b and said current converging connector, wherein a portion I_b of current signal I_i flows through said battery path;

a DC-blocking capacitor in series with said battery impedance Z_b and located along said battery current path to prevent said battery from discharging current through said sensing impedance Z_s;

said sensing current path also having a magnetic field sensor attached with a coupling thereto for measuring the magnitude and phase of I_s and for determining the value of Z_b using the equation

$$Z_b = I' (Z_s + Z_1 + Z_3) + (Z_2 + Z_4)$$

where

$$I' = \frac{I_s}{I_i - I_s},$$

so that:

$$Z_b = \frac{I_s}{I_i - I_s}(Z_s + Z_1 + Z_3) + (Z_2 + Z_4).$$

7. The apparatus for measuring impedance in an electrochemical cell of Claim 6 further comprising an AC-choked load impedance Z_L located along said battery current path in electrical parallel to said battery impedance Z_b, said load impedance Z_L also being located between said connector-wire impedance Z_2 and said connector-wire impedance Z_4 for permitting online measurements of Z_b, Z_L being much larger than Z_s and Z_b.

8. The apparatus for measuring impedance in an electrochemical cell of Claim 6 in which said measuring instrument for measuring the magnitude of I_s includes a magnetic core having a magnetic core path and an air gap that dissects said core path, said sensing impedance Z_s thereby representing a single turn winding on said magnetic core, and a magnetic field sensor being positioned in said air gap, the magnetic flux density to which said magnetic field sensor is exposed is given by the equation

$$B_{gap} = \frac{\mu_0 \mu_{core}}{\ell_{core} + \mu_{core}\ell_{gap}} I_s$$

where B_{gap} is the magnetic flux density of the air gap, ℓ_{gap} is the effective gap length, ℓ_{core} is the effective core flux path length, μ_{core} is the core permeability factor, and μ_o is the permeability of free space.

9. The apparatus for measuring impedance in an electrochemical cell of Claim 6, said apparatus being configured to experimentally determine Z_b by measuring the variable I_s when at least two different calibrated impedances Z_{cal1} and Z_{cal2} are substituted for Z_b using the equation

$$Z_b = I' (Z_s + Z_1 + Z_3) + (Z_2 + Z_4)$$

wherein

$$Z_x \equiv I' Z_3 + Z_1 + Z_3 \text{ and } Z_y \equiv Z_{2+} Z_4$$

so that

$$Z_b = I' Z_x + Z_y$$

resulting in an I_s value of I_1 when Z_{cal1} is substituted for Z_b and resulting in an I_s value of I_2 when Z_{cal2} is substituted for Z_b so that

$$Z_x = \frac{Z_{cal1} - Z_{cal2}}{I_1 - I_2},$$

and so that

$$Z_y = \frac{I_2 Z_{cal1} - I_1 Z_{cal2}}{I_1 - I_2},$$

making the value of Z_b solvable by substitution into the equation

$$Z_b = I' Z_x + Z_y.$$

10. The apparatus for measuring impedance in an electrochemical cell of Claim 6, said apparatus being configured to experimentally determine Z_b by measuring the variable I_s when multiple calibrated impedances Z_{cal1} through Z_{calN} are substituted for Z_b using the equation

$$Z_b = I' (Z_s + Z_1 + Z_3) + (Z_2 + Z_4)$$

wherein

$$Z_x \equiv Z_s + Z_1 + Z_3 \text{ and } Z_y \equiv Z_{2+} Z_4$$

so that

$$Z_b = I' Z_x + Z_y$$

resulting in an I_s value of I_1 when Z_{cal1} is substituted for Z_b and resulting in an I_s value of I_N when Z_{calN} is substituted for Z_b so that

$$Z_{cal1} = I_1 Z_x + Z_y,$$

and so that

$$Z_{calN} = I_N Z_x + Z_y,$$

making the value of Z_x through Z_N solvable and thereby making the value of Z_b solvable by substitution into the equation

$$Z_b = I' Z_x + Z_y.$$

11. A method for measuring impedance in an electrochemical cell comprising:

producing an input current signal I_i with a current generator along a current signal path in a current divider network;

establishing a sensing current path and a battery current path along said current divider network so that said sensing current and battery current paths are electrically parallel to each other and so that said parallel sensing current and battery current paths are in series with said current generator;

locating a measurable sensing impedance Z_s along said sensing current path, locating a connector-wire impedance Z_1 between said current signal path and said sensing impedance Z_s so that a portion of current signal I_i flows from said current signal path through said connector-wire impedance Z_1 to said sensing impedance Z_s, and locating a connector-wire impedance Z_3 between said sensing impedance Z_s and said current signal path so that current flows from said sensing impedance Z_s through said connector-wire impedance Z_3 to said current signal path;

locating a battery impedance Z_b along said battery current path, locating a connector-wire impedance Z_2 between said current signal path and said battery impedance Z_b so that a portion of current signal I_i flows from said current signal path through said connector-wire impedance Z_2 to said battery impedance Z_b, and locating a connector-wire impedance Z_4 between said battery impedance Z_b and said current signal path so that current flows from said battery impedance Z_b through said connector-wire impedance Z_4 to said current signal path; and

locating a DC-blocking capacitor in series with said battery impedance Z_b and located along said battery current path to prevent said battery from discharging current through said sensing impedance Z_s;

instrumentally measuring the magnitude and phase of I_s with a magnetic field sensor and determining the value of Z_b using the equation

$$Z_b = I'(Z_s + Z_1 + Z_3) + (Z_2 + Z_4)$$

where

$$I' = \frac{I_s}{I_i - I_s},$$

so that

$$Z_b = \frac{I_s}{I_i - I_s}(Z_s + Z_1 + Z_3) + (Z_2 + Z_4).$$

12. The method for measuring impedance in an electrochemical cell of Claim 11 in which the magnetic field sensor used for measuring the magnitude and phase of I_s is a Hall effect sensor magnetically coupled to the sensing current path.

13. The apparatus for measuring impedance in an electrochemical cell of Claim 11 in which the magnetic field sensor used for measuring the magnitude and phase of I_s is a magnetoresistive sensor magnetically coupled to the sensing current path.

14. The method for measuring impedance in an electrochemical cell of Claim 11 in which the value of battery impedance Z_b is experimentally determined by measuring the variable I_s when two different calibrated impedances Z_{cal1} and Z_{cal2} are substituted for Z_b using the equation

$$Z_b = I'(Z_s + Z_1 + Z_3) + (Z_2 + Z_4)$$

wherein

$$Z_x \equiv I' Z_3 + Z_1 + Z_3 \text{ and } Z_y \equiv Z_2 + Z_4$$

so that

$$Z_b = I' Z_x + Z_y,$$

resulting in an I_s value of I_1 when Z_{cal1} is substituted for Z_b and resulting in an I_s value of I_2 when Z_{cal2} is substituted for Z_b so that

$$Z_x = \frac{Z_{cal1} - Z_{cal2}}{I_1 - I_2},$$

and so that

$$Z_y = \frac{I_2 Z_{cal1} - I_1 Z_{cal2}}{I_1 - I_2},$$

and then the value of Z_b is solved for by substituting Z_x and Z_y into the equation

$$Z_b = I' Z_x + Z_y.$$

15. The method of measuring impedance in an electrochemical cell of claim 11 in which the instrumental measurement of the magnitude of I_s is accomplished using a magnetic field sensor having a magnetic core that has a magnetic core path and an air gap that dissects said core path, said sensing impedance Z_s thereby representing a single turn winding on said magnetic core, a magnetic field sensor being positioned in said air gap, the magnetic flux density to which said magnetic field sensor is exposed is given by the equation

$$B_{gap} = \frac{\mu_0 \mu_{core}}{\ell_{core} + \mu_{core} \ell_{gap}} I_s .$$

where B_{gap} is the magnetic flux density of the air gap, ℓ_{gap} is the effective gap length, ℓ_{core} is the effective core flux path length, μ_{core} is the core permeability factor, and μ_o is the permeability of free space.

16. The method for measuring impedance in an electrochemical cell of Claim 11 further comprising:

establishing a load impedance Z_L located along said battery current path in electrical parallel to said battery impedance Z_b, said load impedance Z_L also being located between said connector-wire impedance Z_2 and said connector-wire impedance Z_4; and

AC-choking said load impedance Z_L for permitting online measurements of Z_b, Z_L being much larger than Z_s and Z_b.

17. An apparatus for measuring impedance in an electrochemical cell comprising:

a voltage generator for producing an input current signal I_b that flows along a current signal path through a battery having a battery impedance Z_b, said battery being located along said current signal path;

said current signal path having a measurable sensing impedance Z_s located along said current signal path in series with said battery impedance Z_b;

a DC-blocking capacitor in series with said battery impedance Z_b located along said current signal path in series with said battery impedance Z_b and interpositioned along said path between said battery impedance Z_b and said sensing impedance Z_s to prevent said battery from discharging through said sensing impedance Z_s;

said sensing impedance Z_s having a sensing current I_s, a known source voltage V_i, and a magnetic field sensor with a coupling attached thereto for measuring the magnitude and phase of the sensing current I_s using the relation

$$I_s = \frac{V_i}{Z_b + Z_s}$$

making said battery impedance Z_b determinable by the relation

$$Z_b = \frac{V_i - I_s Z_s}{I_s}.$$

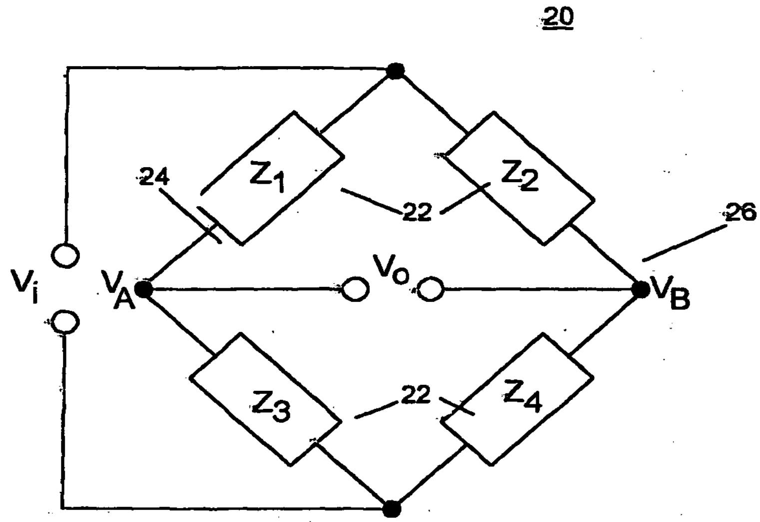

FIG. 1
Prior Art

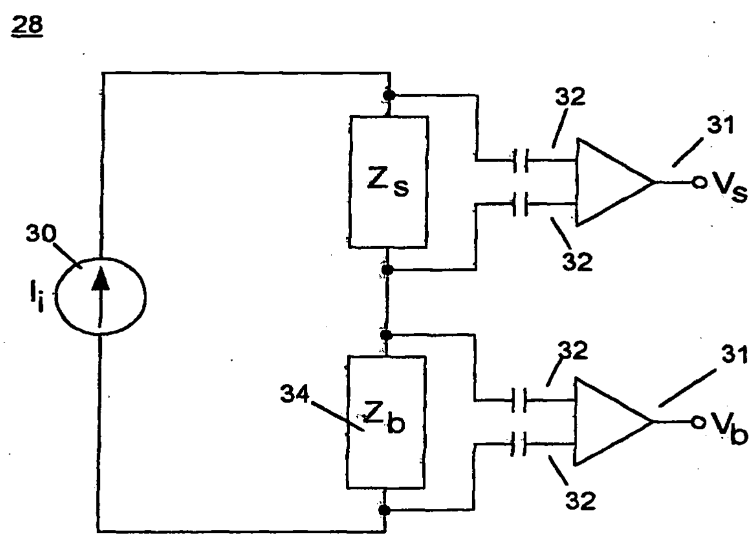

FIG. 2
Prior Art

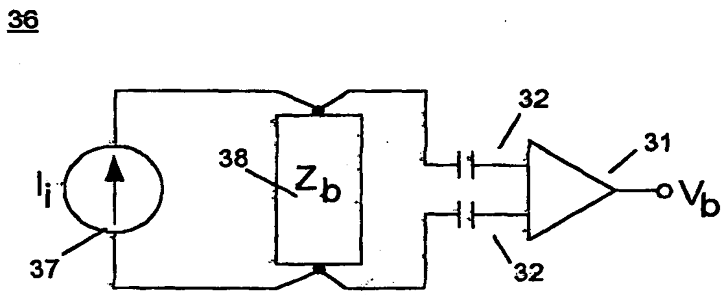

FIG. 3
Prior Art

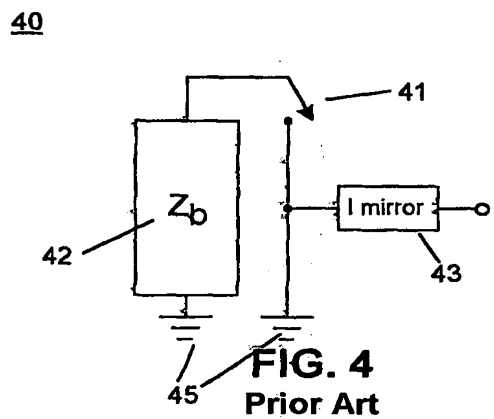

FIG. 4
Prior Art

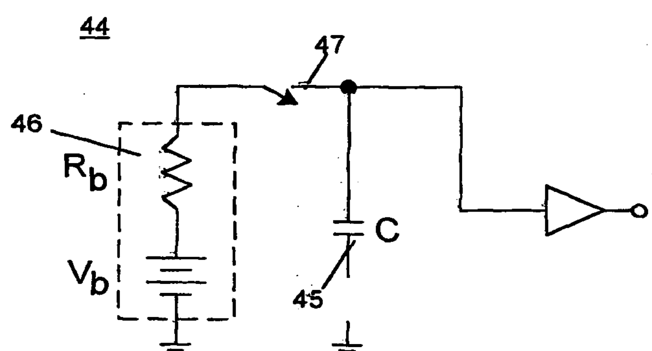

FIG. 5
Prior Art

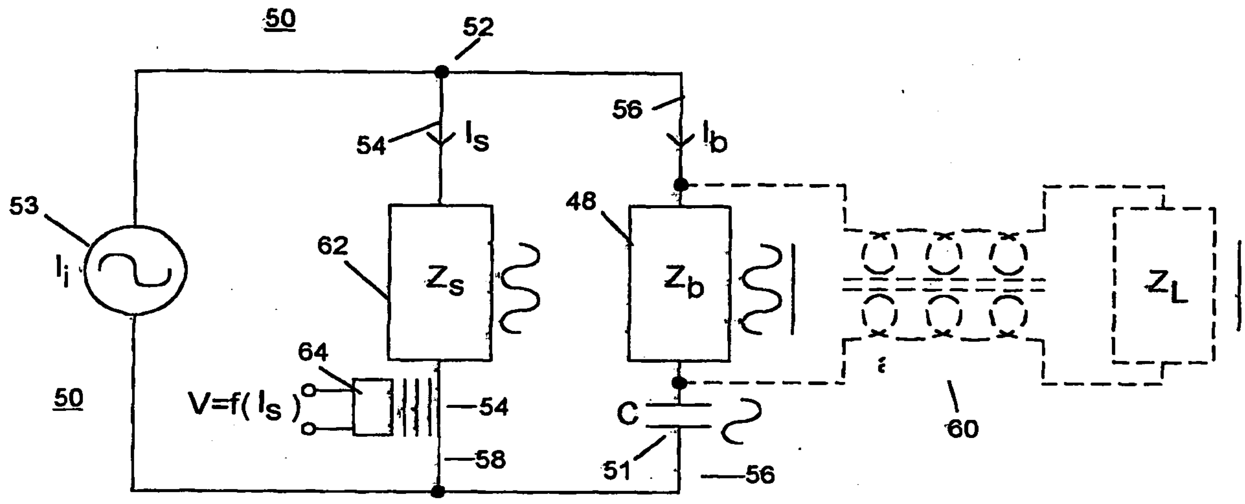
50
52
56
54
I_s
I_b
53
48
62
I_i
Z_s
Z_b
Z_L
64
50
V=f(I_s)
54
C
60
58
51
56

FIG. 6

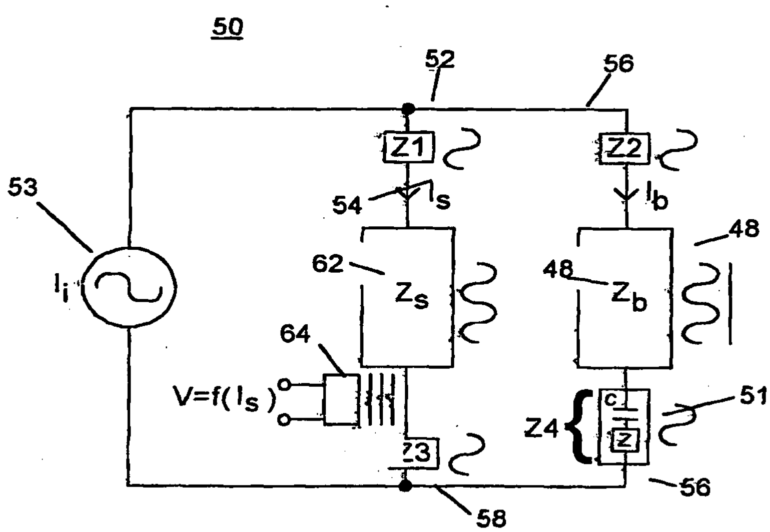
50
52
56
Z1
Z2
53
54
I_s
I_b
48
62
48
I_i
Z_s
Z_b
64
V=f(I_s)
c
51
Z4
Z
Z3
56
58

FIG. 7

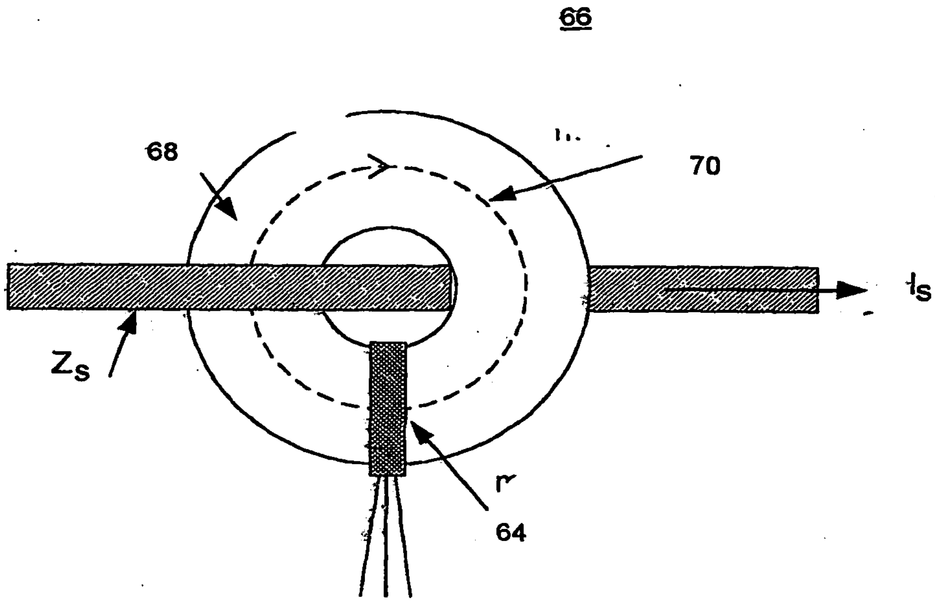

FIG. 8

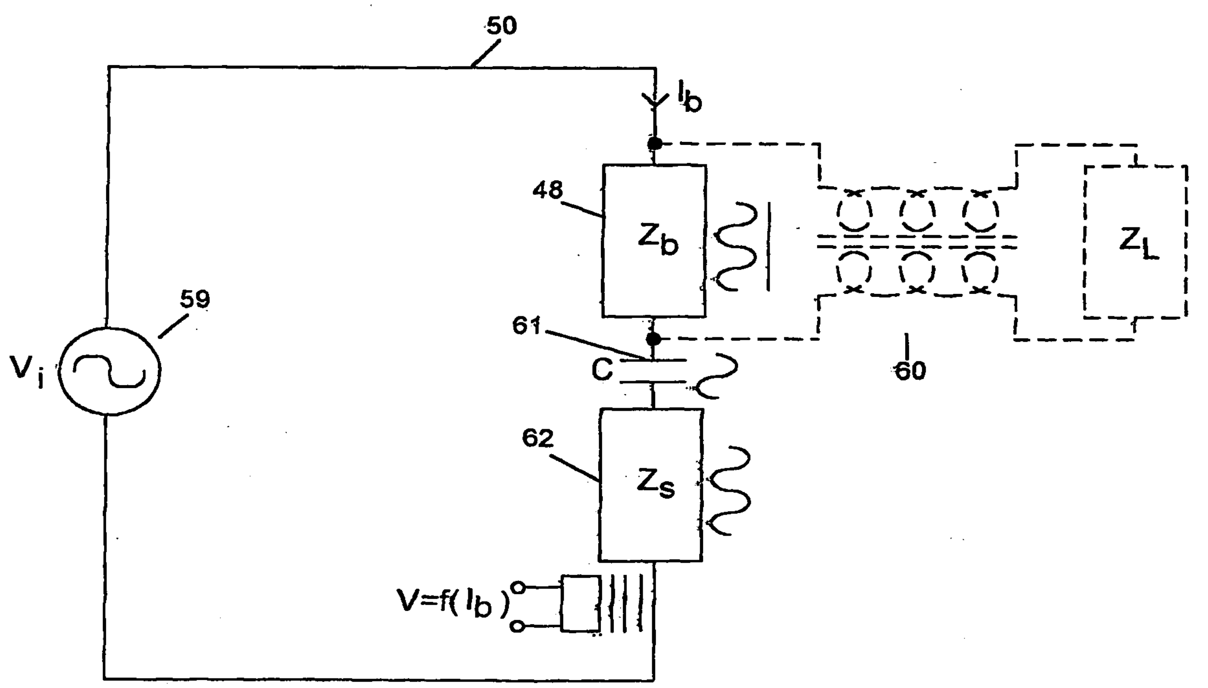

FIG. 9

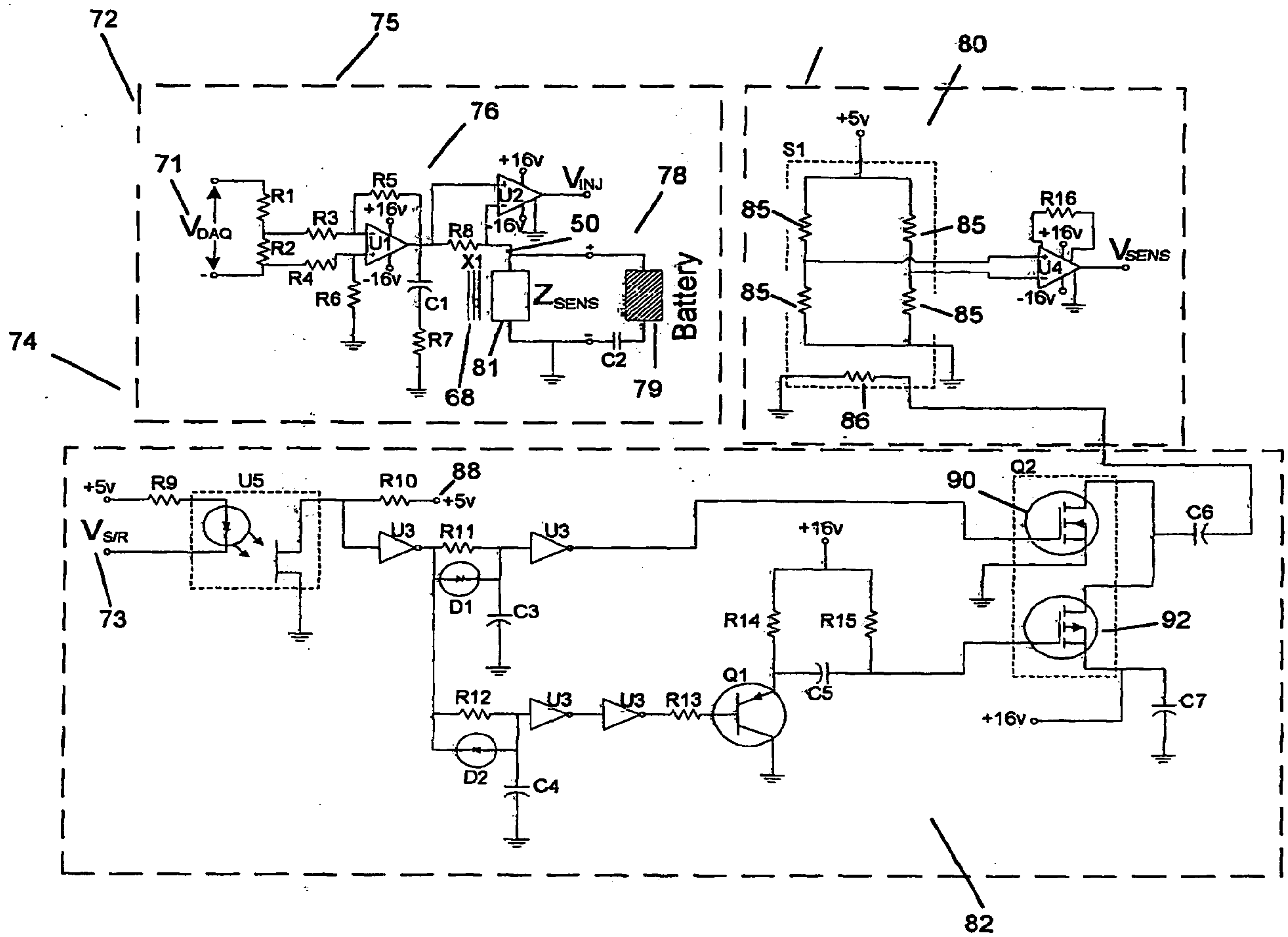
72
75
76
71
V_{DAQ}
R1
R2
R3
R4
R5
+16v
U1
-16v
R6
C1
R7
+16v
U2
-16v
V_{INJ}
R8
X1
50
78
Z_{SENS}
Battery
C2
81
68
79
74
80
+5v
S1
85
85
85
85
R16
+16v
U4
-16v
V_{SENS}
86
+5v
R9
U5
$V_{S/R}$
73
R10
88
+5v
U3
R11
U3
D1
C3
R12
U3
U3
R13
D2
C4
Q1
+16v
R14
R15
C5
90
Q2
C6
92
C7
+16v
82

FIG. 10

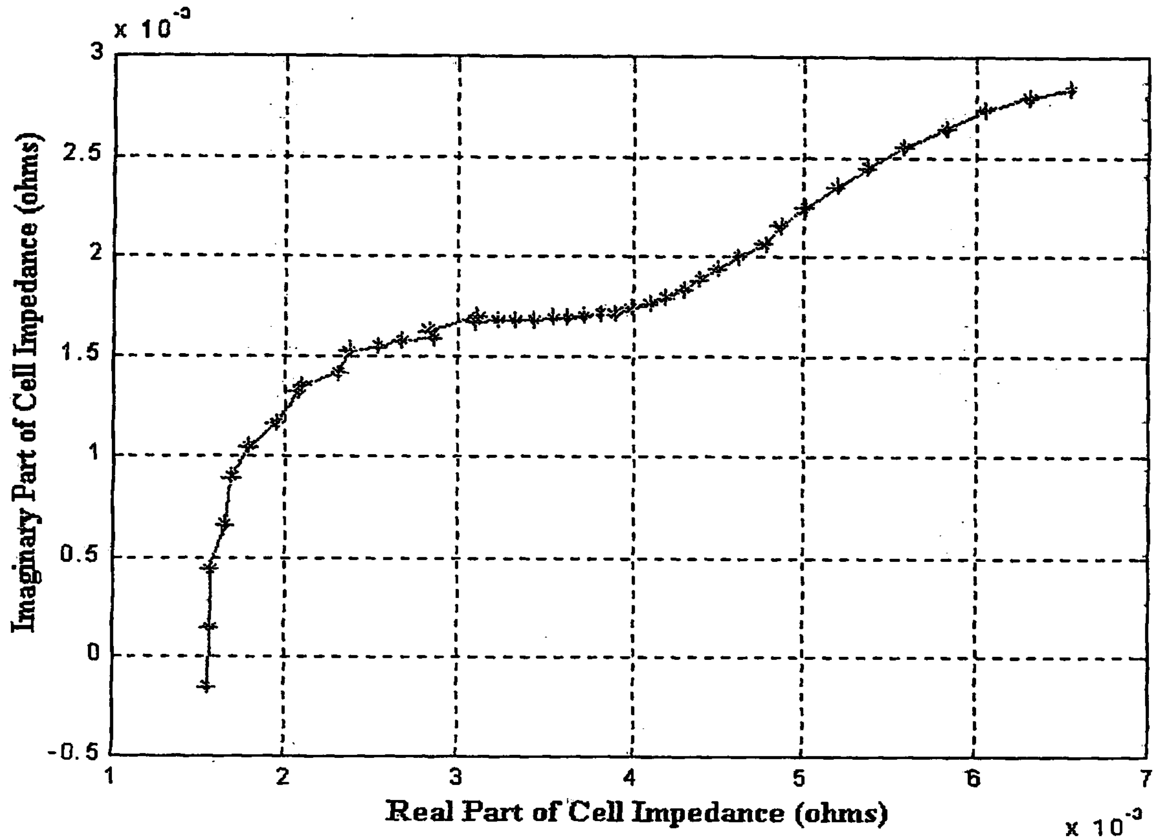
x 10^-3
3
2.5
2
1.5
1
0.5
0
-0.5
Imaginary Part of Cell Impedance (ohms)
1
2
3
4
5
6
7
Real Part of Cell Impedance (ohms)
x 10^-3

FIG. 11

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US00/35044

A. CLASSIFICATION OF SUBJECT MATTER
IPC(7) : G01N 27/416
US CL : 324/430
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
U.S. : 324/426, 324/427, 324/430, 324/434, 324/436, 320/126, 320/134, 320/136

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
East

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US6,002,238A (Champlin) 14 December 1999 (14.12.1999)	1-17
A,E	US6,172,483B1 (Champlin) 09 January 2001 (09.01.2001)	1-17
A	US5,483,165A (Cameron et al.) 09 January 1996 (9.01.1996)	1-17
A	US3,582,774A (Forgacs) 01 June 1971 (01.06.1971)	1-17

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
12 April 2001 (12.04.2001)	09 MAY 2001

Name and mailing address of the ISA/US	Authorized officer
Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	Lawrence Luk
Facsimile No. 703-305-7723	Telephone No. 703-305-0617